

**SENSOR DEVELOPMENT FOR IN-SITU THERMOSPHERIC NEUTRAL  
WIND MEASUREMENTS**

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<b>14. ABSTRACT</b> <p>This report describes progress made in the development of novel new sensors to measure the thermospheric neutral wind velocity from space. The measurements depend upon the supersonic velocity of the spacecraft to determine a velocity vector from measurement of the kinetic energy of the gas along the sensor look direction and the angle of arrival of the gas with respect to that look direction. Two sensors are utilized; one to measure the kinetic energy of the gas and another to measure the arrival angle. The arrival angle is determined from the differential pressure in two adjacent chambers with small entrance apertures. Different pressures in each chamber result from different angles of attack with respect to the chamber apertures. The kinetic energy of the gas with respect to the sensor normal is measured by examining the ions resulting from ionization of the neutrals that flow, undisturbed through an ion source. These two sensors are described in detail with emphasis on the functional verification required to establish the techniques for space flight. In addition to the verification of approach and the detailed design implementation, the requirements for specific accommodations on the Air Force C/NOFS satellite have also been considered.</p>					
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# SENSOR DEVELOPMENT

## THERMOSPHERIC NEUTRAL WIND MEASUREMENTS

### 1. INTRODUCTION

The challenge we have addressed is a specification of the dynamics of the ionosphere and thermosphere during time when severe radio scintillation occurs. This specification must include a description of the neutral air wind velocity and as yet there are no reliable in-situ techniques for accomplishing this goal. We have developed of novel new approaches to make these measurements. This new instrumentation is based on fundamentally sound principles and provides a unique capability to provide measurements essential to a forecast capability for radio communications and navigation system problems. While different techniques for measuring the gas arrival angle from satellites have been described [Spencer et al., 1973, Hanson et al., 1992], measurement of the neutral gas kinetic energy has met with limited success. A clear need was apparent for more laboratory work to optimize the design characteristics of such instruments. The work was aimed at examining the characteristics of ionization sources, ion optics at the output of the ion source, and detectors. In the upper atmosphere a satellite moves supersonically through the neutral gas and thus the spacecraft motion dominates the neutral gas velocity with respect to the sensor. Then three mutually perpendicular components of the neutral wind velocity can be measured using sensors designed to view the atmosphere approximately along the direction of motion of an orbiting satellite. One sensor, called the ram wind sensor (RWS) should measure the neutral gas velocity along the sensor look direction called the ram wind component. Another should measure the angle of arrival of the neutral gas in two mutually perpendicular planes with respect to the sensor look direction. We call this the cross-track sensor (CTS). A simple tangential relationship between these two parameters allows the cross-track wind components to be derived as shown in figure 1.

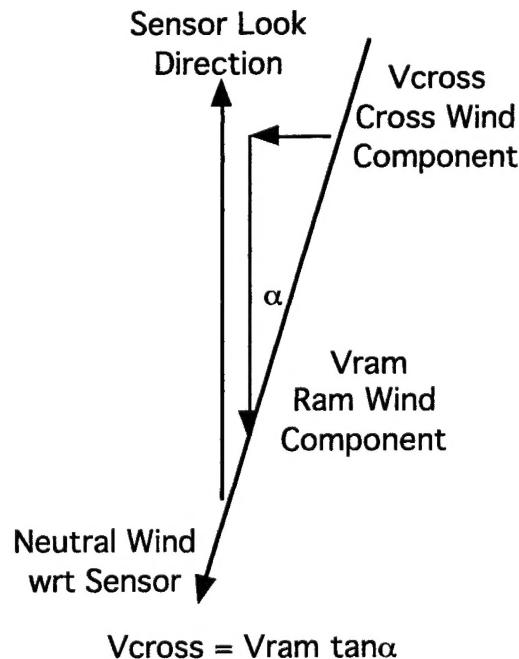


Figure 1. Geometrical Relationship Between Cross-Track and Ram Wind Components

## 2. SENSOR DEVELOPMENT

### 2.1 Cross-Wind Measurements

The approach to be examined here is a conceptually simple device that utilizes the relationship between the neutral gas pressure in an enclosure with a small entrance aperture and the angle between the neutral gas stream and the aperture normal.

In steady state the in-flux of ambient particles is matched by the outflow of particles in equilibrium with the chamber walls. Thus

$$n_c = 4 \frac{\phi_a}{\bar{v}_c} = n_a \frac{\bar{v}_a}{\bar{v}_c} \left[ e^{-s^2} + \sqrt{\pi} s (1 + \text{erf}(s)) \right]$$

Then the ambient and chamber pressures are related by the expression

$$P_c = P_a \left[ e^{-s^2} + \sqrt{\pi} s (1 + \text{erf}(s)) \right] \left( \frac{T_c}{T_a} \right)^{\frac{1}{2}} \left( \frac{m_c}{m_a} \right)^{\frac{1}{2}} \quad (1)$$

Where

$$s = \frac{v_r \cos \alpha}{\bar{v}_a} = \beta v_r \cos \alpha$$

$\bar{v}_a = \sqrt{2kT_a/m_a}$  is the most probable thermal velocity of the particles outside the chamber

$v_r$  is the sensor ram velocity

$\alpha$  is the angle between the normal

to the entrance aperture and the sensor ram velocity

For supersonic flow where  $s \gg 1$  equation (1) simplifies to

$$P_c = 2\sqrt{\pi} \beta v_r \cos \alpha \left( \frac{T_c}{T_a} \right)^{\frac{1}{2}} \left( \frac{m_c}{m_a} \right)^{\frac{1}{2}} P_a \quad (2)$$

$$\text{With } \alpha = 0; \beta v_r = 7; \frac{T_c}{T_a} = 0.25; \frac{m_c}{m_a} = 1 \quad P_c \approx 12.5 P_a$$

Suppose the pressure in two aligned chambers with aperture normals making angles plus and minus  $\alpha$  with the velocity vector, is measured with ion gauges that utilize logarithmic electrometers providing inputs to a linear difference amplifier. Then, for a gas arrival angle,  $\epsilon$  with respect to the ram direction, the difference amplifier output is given by

$$V_d = G_d C \ln \left( \frac{P_1}{P_2} \right) = G_d C \ln \left( \frac{\cos(\alpha - \epsilon)}{\cos(\alpha + \epsilon)} \right)$$

Where the overall gain  $C$ , and offset of the pressure measurement system are assumed to be the same.  $G_d$  is the difference amplifier gain.

Expanding the cosine products, dividing top and bottom inside the log by  $\cos \alpha \cos \epsilon$  we arrive at the expression

$$\tan \epsilon = \frac{1}{\tan \alpha} \frac{1 - 10^{\frac{V_d}{G_d C}}}{1 + 10^{\frac{V_d}{G_d C}}}$$

This precise expression can be simplified by expanding the logarithms to first order to yield

$$\tan \epsilon \approx \frac{1}{2G_d C \log(10) \tan \alpha} V_d$$

Figure 2 shows a cross-sectional drawing of a differential pressure gauge that has been designed during this research period. The design is based on the original concepts described by Hanson et al [1992] but with important modifications for the flight opportunity offered by the Communications/Navigation Outage Forecast System (C/NOFS). Four chambers are utilized in pairs to provide two orthogonal arrival angle measurements. Separate logarithmic amplifiers provide the outputs from the four pressure gauges. Offsets in these gauges are removed by noting the outputs when the pressure in all the chambers is equalized by opening a valve that provides a large aperture connection between all the chambers.

During this research period we have evaluated the performance of the Bayard-Alpert pressure gauges to be used in each of the four chambers, and of the solenoid actuated pressure-equalization valve used to establish the absolute zero for the difference amplifier outputs.

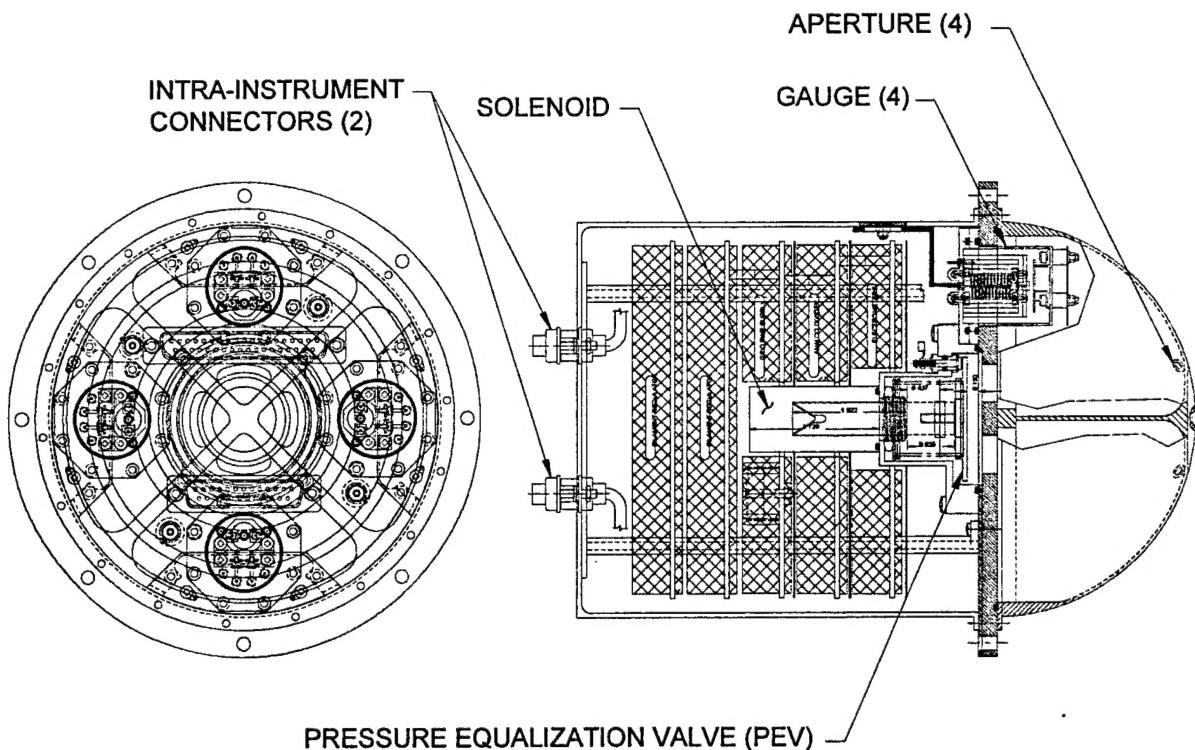


Figure 2. Schematic Illustration of Differential Pressure Measurement to Provide Cross-Track Wind Component.

### 2.1.1 Pressure Gauge

A Bayard-Alpert pressure gauge allows for the simplest measure of pressure over the required range and can be easily constructed in a miniature package with redundant hot filaments for the ionization source. The gauge enclosure is designed to ensure that no streaming ambient gas has access to the gauge. Figure 3 illustrates the configuration of the filament and grids.

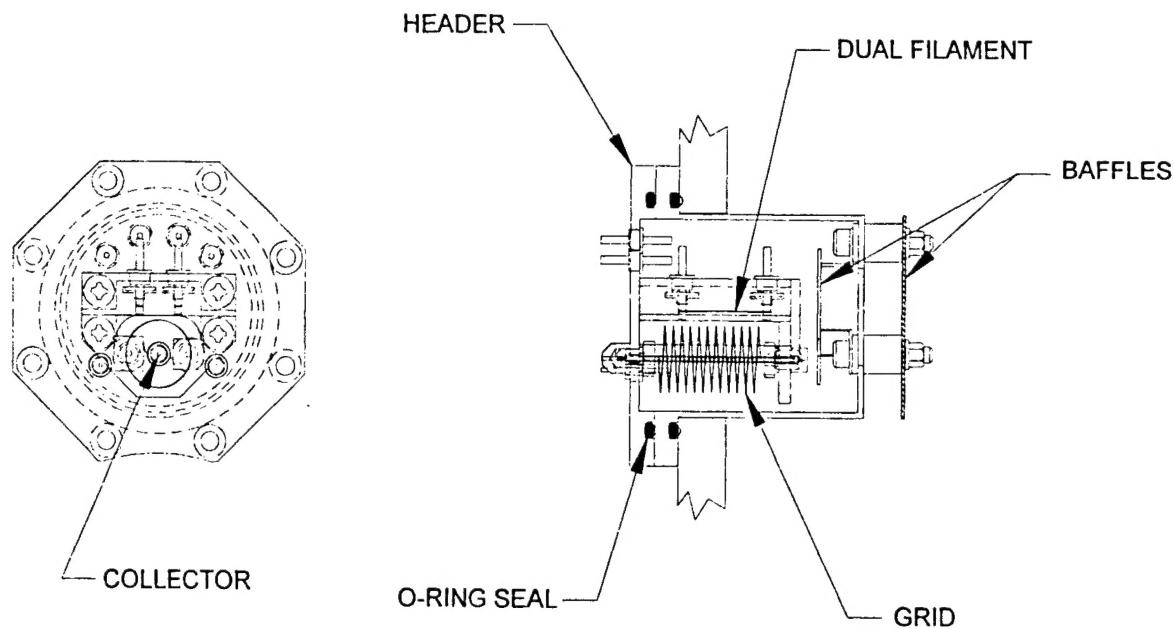


Figure 3. Bayert-Alpert Pressure Gauge Utilized in the Cross-Track Wind Sensor.

Figure 4 shows the output current versus pressure from the gauge operated with 25  $\mu$ A emission current. Typical ram pressure increases for this device lie between 10 and 20, thus we expect that for operation between the exobase and 350 km altitude the pressure will range from  $10^{-8}$  to  $10^{-6}$  Torr. A 97%-3% Tungsten-Rhenium filament is expected to provide a lifetime in excess of 2 years in this environment [Mauersberger and Olsen, 1973]

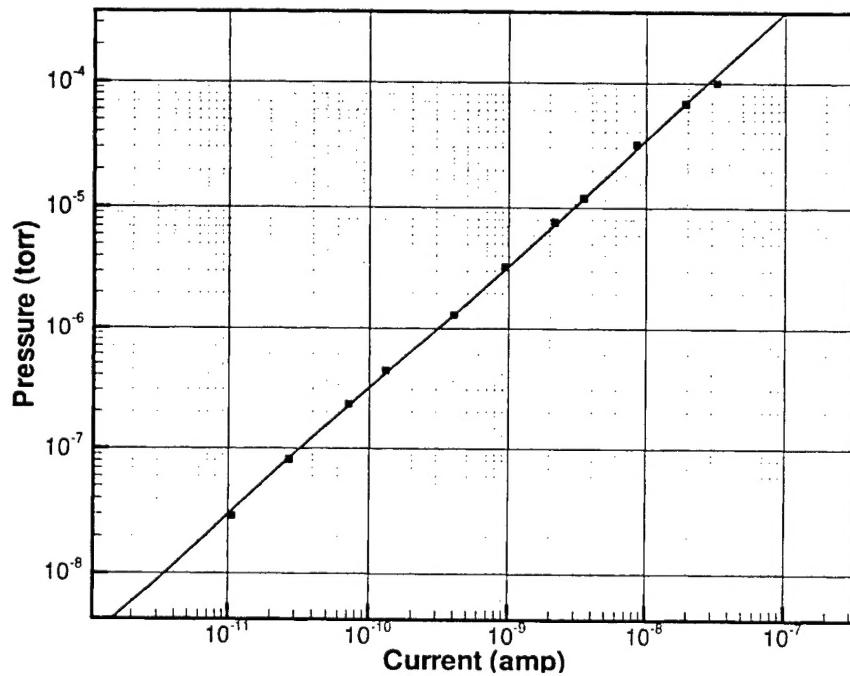


Figure 4 Pressure Gauge Performance at 25  $\mu$ A Emission Currents.

### 2.1.2 Chamber and Entrance Aperture Design

As was discussed in the operating principles the chamber pressure depends upon the cosine of the angle between the neutral gas stream and the aperture normal. Near zero angle of attack the change in pressure as a function of angle is quite weak. However, a ram looking aperture affords a large pressure enhancement and the instrument is relatively uncontaminated from neutral particles scattered from the spacecraft surface in this case. It is clear that we must arrange an offset angle between the aperture normal and the ram neutral stream such that an adequate sensitivity to the angle of attack is obtained. But we must also retain a suitable ram pressure enhancement and minimize the effects of scattered particles into the aperture.

The chamber volume and aperture size also affects the instrument performance. There are several considerations here. One is the pumping speed of the device. That is a determination of the time taken for a new equilibrium pressure to be established due to a change in the neutral stream arrival angle. This pumping speed depends upon the ratio of the chamber volume to the aperture area and the equilibrium temperature of the gas in the chamber. Thus, the chamber dimensions must be minimized but should be several mean free paths for the neutral gas to ensure that equilibrium with the walls is reached. The aperture size should be maximized but we must ensure that the distance from the aperture edge to the chamber walls is large enough.

To examine these properties we have constructed a numerical simulation of the pressure gauge performance allowing the sensor dimensions and the aperture position to be varied for different satellite velocities in different ambient conditions. Figure 5 shows an example output from the simulator.

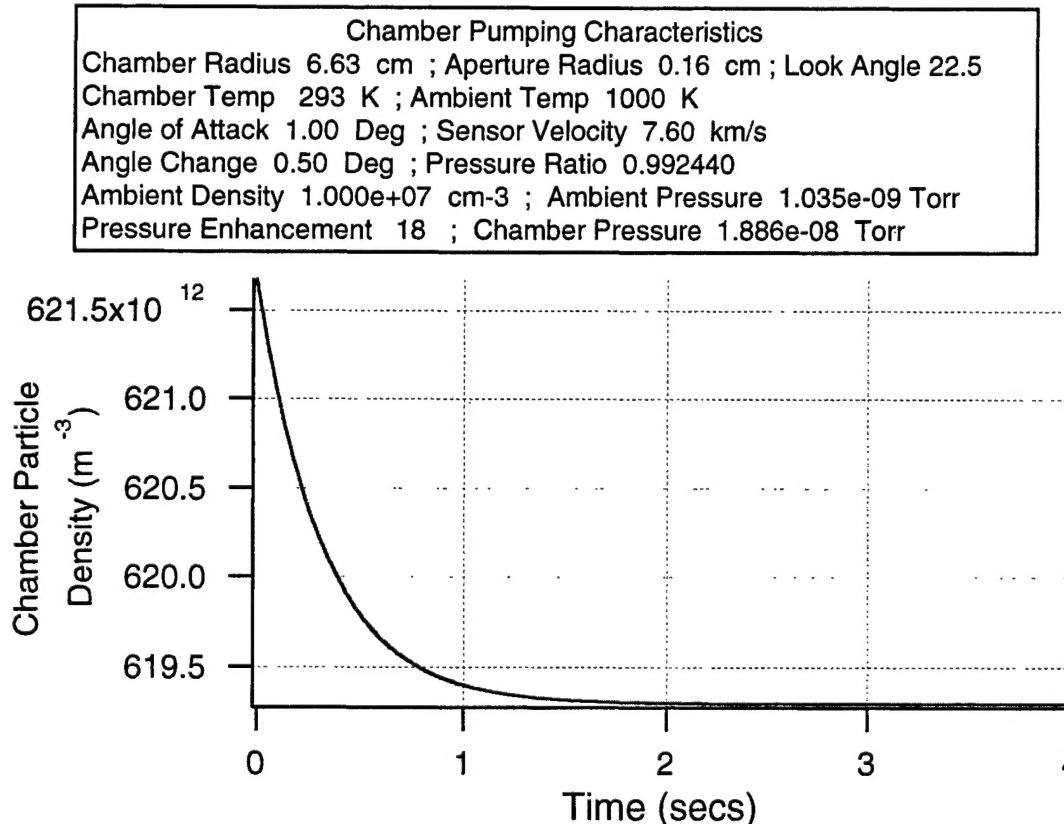


Figure 5. Instrument Simulation Showing Pumping Speed for typical F-Region Thermosphere Conditions.

These simulations show that we can be quite confident that the instrument will resolve spatial variations in the neutral wind with magnitudes of 10m/sec (0.1 degrees) in a fraction of a second.

### 2.1.3 Absolute Zero.

The neutral gas arrival angle is determined from the ratio of logarithmic electrometers that respond to the pressure in the chambers. The response of these electrometers and the gauges may not be the same and may change during the lifetime of a typical satellite mission. In order to take account of these differing electrometer and gauge characteristics it is necessary to periodically establish the difference amplifier output when the chamber pressures are known to be equal. A pressure equalization valve at the rear of all the chambers accomplishes this. The valve is operated by a solenoid. It has been carefully designed to be powered momentarily to open the valve and then to minimize the power to maintain a "holding force." In this manner the power utilization is minimized. The valve is spring loaded so that when the power is removed the valve closes. Figure 6 shows the solenoid and valve assembly undergoing life tests in the laboratory.

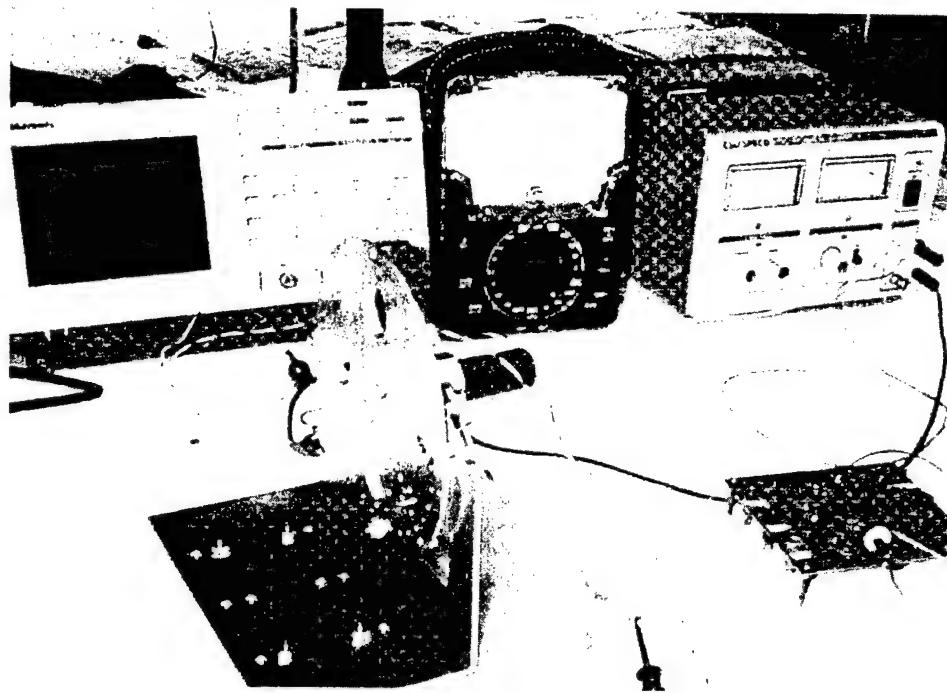


Figure 6. Pressure Equalization Valve and Test Assembly for Bench Life Testing.

### 2.2 Ram Wind Measurements

The ram wind sensor is designed to measure the kinetic energy of the incoming neutral gas. The neutral gas is itself detected by first ionizing a fraction of the incoming neutrals and then detecting the resulting ions. To successfully relate the measured kinetic energy of the ions to the kinetic energy of the parent neutrals it is necessary to ensure that the neutral gas flows relatively unimpeded through the instrument. In addition the ion source should not significantly affect the ram energy of the incoming neutrals or the resultant ions. Figure 7 shows a schematic cross-section of the RWS illustrating the key design characteristics.

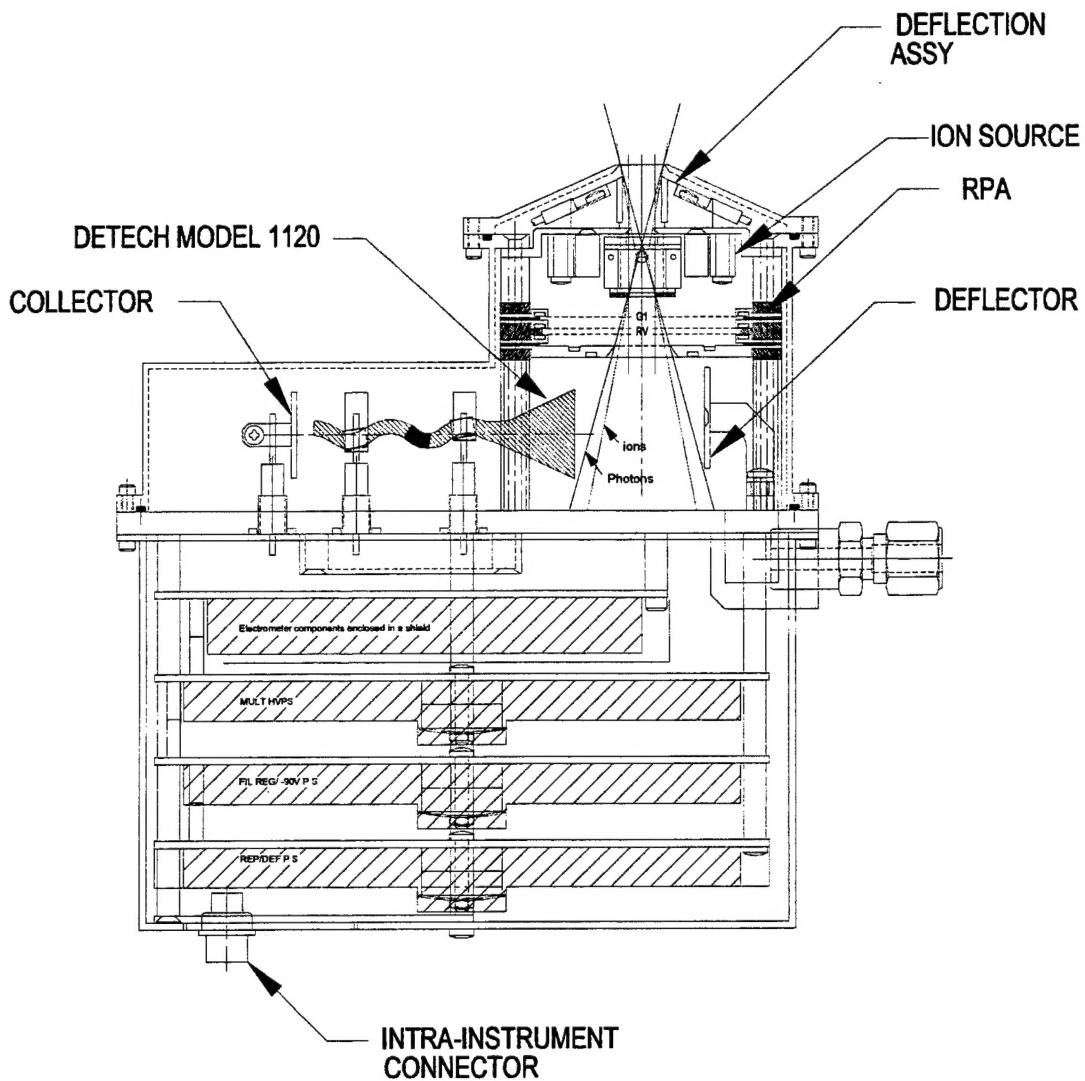


Figure 7. Cross Sectional Drawing of Ram Wind Sensor Showing Ion and Photon Trajectories.

### 2.2.1 Collimator

In practice the spacecraft velocity will dominate the neutral velocity with respect to the sensor. Thus, if the sensor look direction is aligned approximately along the vehicle velocity then the neutral gas arrival angle will be within about 10 degrees of the sensor look direction. The sensor entrance and ion-source entrance are designed to provide this acceptance angle and to ensure that all particles within this acceptance cone have an unimpeded path to the rear of the instrument.

### 2.2.2 Ion Source

The ion source should have the required efficiency to produce an ion flux over the expected neutral density range that will allow the resulting ion signal to be subjected to retarding potential analysis. At the same time we would like to minimize the space charge

surrounding the electron beam used for ionization. It should be remembered that the ion source efficiency will determine the entrance aperture size and thus the sensor dimensions.

### 2.2.3 Retarding Potential Analyzer

The retarding potential analyzer section has a planar geometry similar to the more conventional grid structure used in planar ion sensors that have flown and operated successfully for many years. In the thermosphere the major neutral species are atomic oxygen and molecular oxygen and nitrogen. At spacecraft orbital velocities these species have kinetic energies near 5 eV and 10 eV respectively. It is thus easy to distinguish these species with an energy analysis. Ions approaching the grid stack at non-normal incidence will be displaced when passing through the retarding grids. Thus, the input aperture to the detector must be sized to accommodate the maximum acceptable displacement.

### 2.2.4 Detector

In the altitude range where we wish the sensor to operate an electron multiplier will be required to detect the retarded ion current beyond the source. The multiplier must be located away from the neutral stream through the sensor and in a manner that protects it from solar photons. The ion optics that will allow detection of the ions exiting the RPA needs to be studied. The multiplier will be biased at potentials near -1600 volts and the electric field between this biased surface and the grounded sensor walls provides the focussing properties that are required.

Figure 8 shows the trajectories of ions leaving the source and passing through the retarding grid to the detector. We have sized the detector entrance aperture to allow ions within a 7-degree acceptance cone to be detected if they have energies greater than 0.01 V beyond the retarding grid potential.

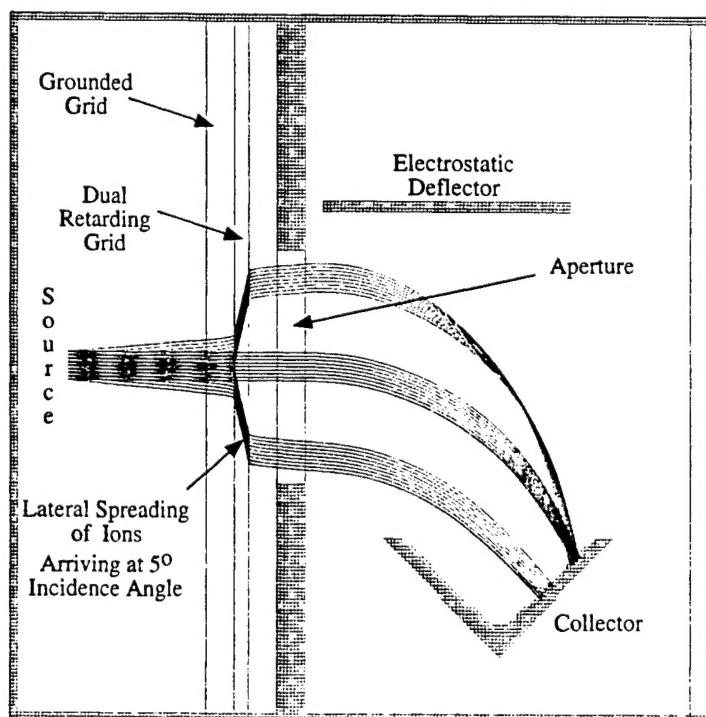


Figure 8. Ion Optics Simulation of Trajectories for Non-Normal Incidence Through the RWS

### **2.3 Specific Instrument Design and Accommodations Issues**

During the course of this development work we have breadboarded and tested key elements of a flight configuration. These initiatives were in support of the flight opportunity presented by the C/NOFS satellite.

Power supplies and filament regulators for the ion sources in the sensors are of primary consideration and thus the test and evaluation of these subsystems is a high priority. Having successfully accomplished this task it is also prudent to demonstrate our ability to resolve the ion-source characteristics with a electron multiplier operating in the analog mode.

Figure 9 shows the output of several laboratory tests designed to demonstrate this capability. With intrinsic ram energy in the ion beam, a draw-out potential is used to move the ions to the detector. However, a characteristic energy distribution for ions in the source is easily described by the retarding potential analysis shown. Sufficient gain is obtained with the multiplier biased at only 800 V while operation at 1200 V provides additional sensitivity. The background current level in flight is expected to be significantly lower than that seen in the laboratory.

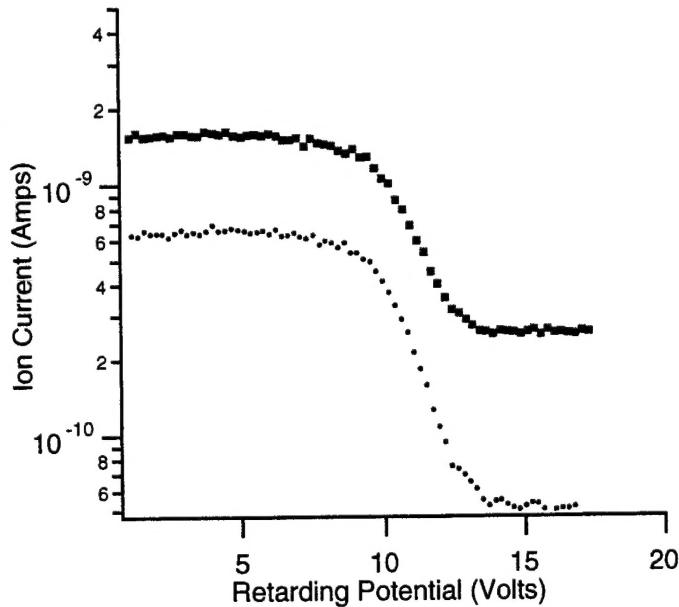


Figure 9. I-V Characteristics From the RWS for Different Multiplier Voltages.

### **3. CONCLUSIONS**

This research effort has resulted in the design and verification of a robust space instrument to measure the F-region neutral wind vector. In addition to the conceptual design laboratory evaluation and computational simulations we have also provided instrument requirements and interface specifications allowing the instrument to be accommodated on the C/NOFS satellite. The research and engineering completed to date provide every confidence that both the approach and the implementation plan for in-situ measurement of the neutral wind are well conceived. Future activities will require the continuation of life and verification testing as well as fabrication of flight assemblies. We can now confidently look forward to obtaining essential measurements of the equatorial F-region neutral wind during the C/NOFS program.

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